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FINAL REPORT
BALLISTIC SIGNATURE IDENTIFICATION
SYSTEM STUDY
May 12, 1976

Submitted to:
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Johnson Space Center
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ABSTRACT

This report documents Phase I of a UNITECH research project directed toward development of a high speed automatic process to be used to match gun barrel signatures imparted to fired bullets. This project was contracted by NASA-JSC and defined in paragraph 3.2.1.a of the contract task description. An optical projection technique has been devised to produce and photograph a planar image of the entire signature, and the phototransparency produced is subjected to analysis using digital Fourier transform techniques. The success of this approach appears to be limited primarily by the accuracy of the photographic step since no significant processing limitations have been encountered.

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I. INTRODUCTION

In recent years, some of the most visible contributions by the engineering community to the overall improvement in man's quality of life have been through application of computer based automatic machinery to highly sophisticated and otherwise time-consuming tasks. Generally, these have been tasks which had long been well understood, but for which contemporary technology could not support execution of the tasks on the scale required. A good example of such a task is the Forensics application of ballistic slug identification. The generation of legal evidence by studying gun barrel signatures imparted to fired ballistic slugs, popularly termed "ballistics", is still considered to be a modern forensic procedure, but large-scale application of the technique has been prevented by the length and complexity of the process. Still basically a laboratory technique, the procedure is one which is performed manually by a trained technician and calls for moderate skill with a microscope and considerable personal judgment. Typically, ballistic analysis is not performed routinely because of limitations on time and trained personnel, in spite of the fact that most investigators of crimes involving firearms eagerly seek ballistics assistance. Therefore, ballistics is a good example of a process which has not yet made the transition from laboratory demonstration to production level application and can benefit significantly from high speed automation.

The central element in ballistics technology is the gun barrel signature. During manufacture, the bore of a gun barrel is drilled into a piece of solid steel and then finished, usually with rifling grooves added, by means of a series of reaming and polishing operations. Although in the more expensive weapons this polishing is very thorough, it is impossible to completely remove all surface roughness. When a bullet is fired through the barrel, the microscopic bumps and ridges along the bore literally scrape tiny grooves along the length of the bullet as it passes through, so that it collects a record of the bore topography. This record is incomplete, insomuch that it reveals little about the longitudinal position of bore surface features; instead it contains the composite of the circumferential or angular positions of bore features. The effect of rifling is to contribute to repeatability of the bore signature from one bullet to the next. The rifle grooves effectively lock the bullet in a fixed angular relationship to the bore so that as the bullet moves along collecting markings, it cannot randomly turn about its axis which would destroy any record of angular relationships between features at opposite ends of the bore. In addition, the rifling process is one which leaves still more characteristic markings on the bore surface. In summary, it is the angular relationship of longitudinal marks on the bullet which constitutes the unique gun barrel signature and provides a basis for determining whether or not two bullets have been fired from the same gun barrel.

Ballistic analysis is currently performed optically. A weapon which is recovered during the course of an investigation is test fired into a capture box, usually filled with cotton string or sometimes soap. The resulting test slugs are then assumed to possess a representative signature of the gun barrel under consideration. One of the test slugs is mounted on one turret of a split image comparison microscope while an evidence slug recovered from the scene of a crime is mounted on the other. Figure 1 is a photograph of the image viewed by the ballistics laboratory technician. Each half of the split image field shows a magnified portion of the side of one of the slugs. The technician rotates one of the slugs with its turret until he sees a prominent feature. He then rotates the other slug in search of the same feature. When he finds it, he carefully aligns the prominent features in the two halves of the split image and then examines the positional alignment of the minor markings present on the two slugs. If most of the markings in his field of view appear to correspond on both slugs, the technician carefully rotates both slugs together, examining the entire 360 degrees of the signature. Inevitably there will be some marks which cannot be matched on both slugs, and it is this disparity which must be evaluated by the technician based upon previous experience. Should the evidence slug be damaged, as is often the case, the evaluation becomes still more difficult since the decision must be made from only a partial signature.

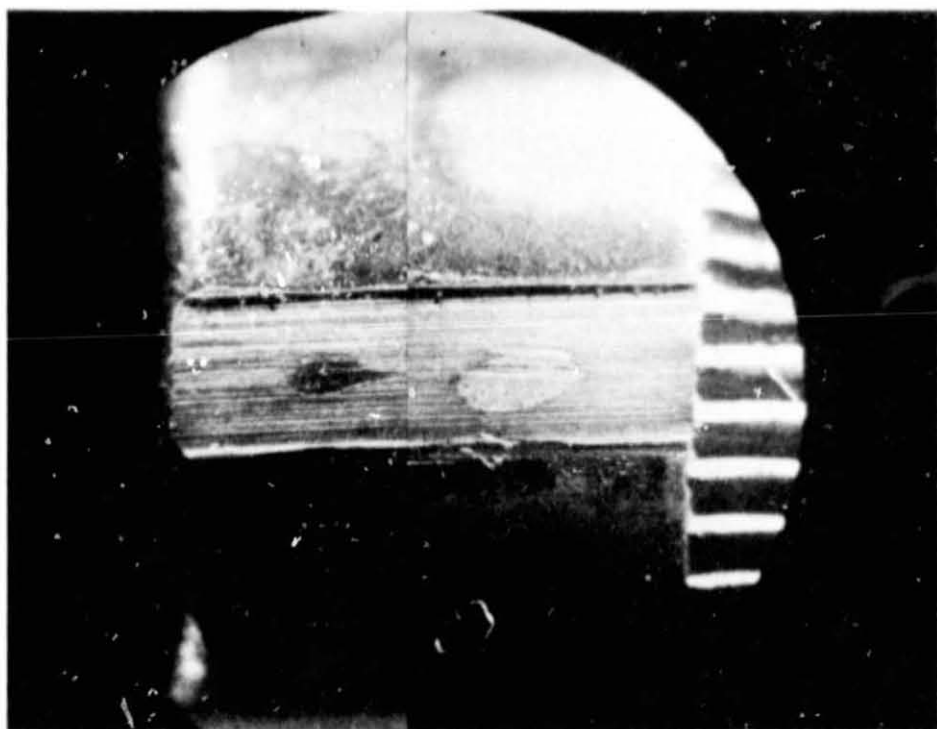


FIGURE 1
PHOTOGRAPH OF GROOVE AREAS OF TWO
BULLETS DISPLAYED BY A COMPARISON MICROSCOPE

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ORIGINAL PAGE IS POOR

The object of the research effort documented herein is not to develop an automatic system which can perform signature comparisons as accurately as humans can. Instead, it is hoped that a high speed system will be developed which can accurately perform coarse comparisons to limit the number of bullets which must be examined by human technicians in order to provide a more widespread monitor of weapon related crimes. At present, ballistics can only handle the task of confirming or disputing the investigator's hypotheses. If a high capacity screening system were available, routine gun barrel signature checks could be performed on a city-, state-, or perhaps nationwide scale so that crimes related by a common weapon could be detected automatically. This capability could elevate the role of ballistics from one of evidence support and confirmation to one of multiple offense detection.

The next chapter, titled Problem Analysis, provides an overview of three methods which have been proposed to compare signatures. One of these methods is chosen to be the foundation for this research project, and the reasoning behind that selection is presented. Chapter Three is called Data Extraction and deals with those considerations affecting the spatial data sampling technique. Chapter Four describes the signal processing techniques applied to the signatures and presents the information obtained therefrom. The last chapter summarizes the progress made toward matching signatures and discusses limitations encountered and means by which these may be overcome.

II. PROBLEM ANALYSIS

The gun barrel signature as found on a bullet is a three-dimensional pattern, albeit a somewhat simplified one because it is restricted to the surface of a relatively simple geometric body. A further simplifying observation is that the pattern is situated on a single continuous surface. One of the limitations inherent in visual analysis of three-dimensional patterns is that only part of the pattern can be viewed at one time. It is this limitation that causes the ballistics technician to turn the bullet to locate the salient features. At least from an optical standpoint, such patterns are much more easily recognized when they are planar. Several techniques have been suggested for "unwrapping" the signature from the bullet. The most direct method is used by the profilometer, which consists of a stylus whose vertical travel is recorded as it follows the surface of a bullet which is turned beneath it. A lead screw moves the stylus along the length of the bullet as the bullet turns so that the entire cylindrical surface can be probed. In many ways the profilometer resembles the original Edison phonograph. Another approach makes use of the same basic mechanical arrangement, but the bullet surface features are illuminated by a narrow, highly collimated laser beam, and the scattered light is detected by a photomultiplier. A third scheme produces a reflected optical image of the entire signature while avoiding the necessity for a rotating mechanism. Figure 2 is a cross-sectional diagram of a bullet centered in a conical reflector. This reflector projects an annular image of the bullet's cylindrical surface which can be recorded on film for subsequent digital processing. Figure 3 is a photograph of a jacketed, hollow-point bullet's image produced in this manner.

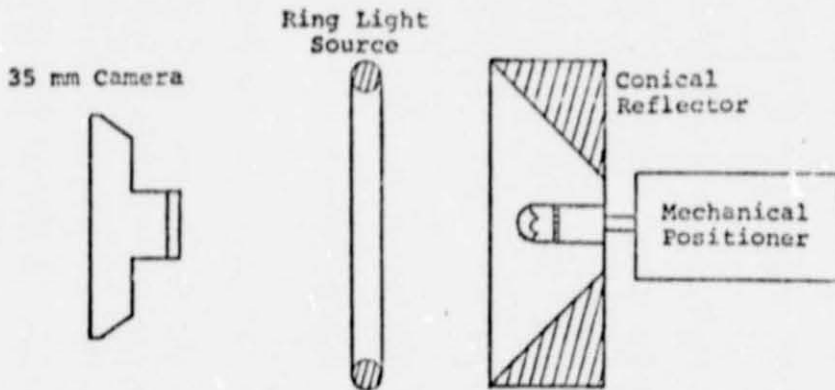


FIGURE 2
DIAGRAM OF THE BULLET PHOTOGRAPHIC SYSTEM

The third method is the one chosen for this project. It has the advantages that a planar image displaying the entire signature is produced, and a photographic record is easily obtained which permits both digital and optical processing. Digital processing begins at this point by scanning a photo-transparency of the signature image with a microdensitometer. The microdensitometer measures optical density of the photo-transparency points defined by a two-dimensional X-Y grid. A density value is generated and stored on digital magnetic tape for each X-Y coordinate pair. Signatures digitized in this manner can then be compared by cross-correlation or matched filter techniques.



FIGURE 3
PHOTOGRAPH OF A HOLLOW-POINT BULLET WITH
SIGNATURE VISIBLE IN THE CONICAL REFLECTOR

The phototransparency can also be used to match signatures in a totally optical system. This approach exploits the capability of lenses to produce two-dimensional Fourier transformations. Figure 4 is a diagram depicting an optical system which will produce the two-dimensional Fourier transform of a phototransparency. Goodman [1]^{*} explains that a

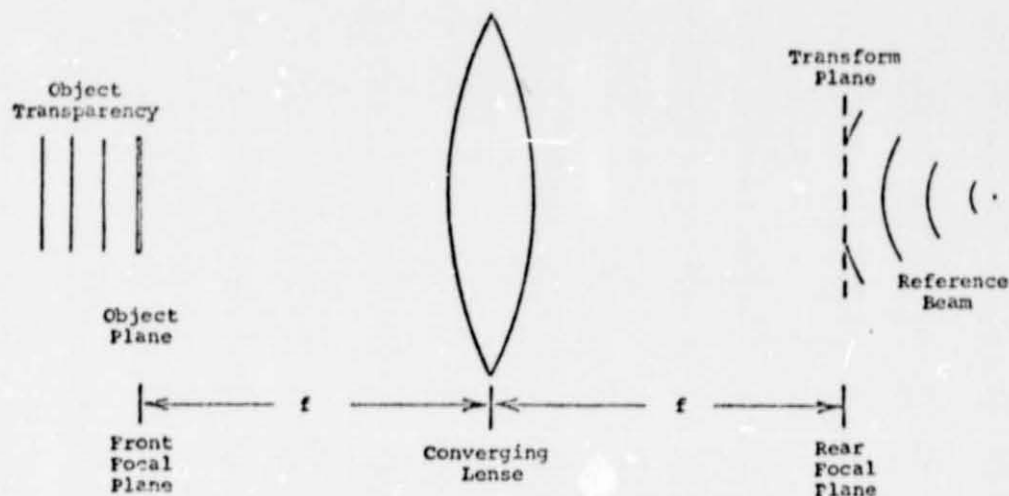


FIGURE 4
DIAGRAM OF AN OPTICAL FOURIER PROCESSING SYSTEM

converging (convex) lens produces the exact two-dimensional Fourier transform, in its rear focal plane, of a two-dimensional object image located in its front focal plane. The object image is assumed to be illuminated by a monochromatic plane wave. In reality, the range of the transform is restricted to the primary lobe of the Fresnel diffraction pattern for the lens aperture, but this limitation can be easily accommodated if the lens can be made large when compared with the object image. If a diverging coherent reference beam is directed onto a photographic

^{*}Bracketed numbers correspond to reference numbers in the bibliography.

emulsion located in the transform plane in Figure 4, a holographic matched filter for the object transparency will be recorded. For optical matched filter processing, the filter phototransparency is replaced in the transform plane of the same optical system but no reference beam is used. If the object transparency contains the image to which the holographic filter is matched then a reference beam will be holographically reconstructed which is focused on the focal point of the original diverging reference beam. A photo detector located at that point serves to signal that a match has occurred.

Still another processing method is available for transparencies which is an optical-digital hybrid. In this method, the converging lens is used to generate the Fourier transform just as in the totally optical system, but it projects the spectrum onto a photodiode detector array situated in the rear focal plane. Each diode in the array produces a voltage proportional to the intensity of light striking it, so that if the array outputs are sampled and digitized, a digital two-dimensional power spectrum is obtained. While a power spectrum cannot be used to perform cross-correlation, it might be useful to perform coarse signature screening of the basis of power spectral comparison alone. If a digital data library of stored normalized power spectra were available in a digital computer interfaced to the diode array, then it would be a simple matter to insert a transparency of a new signature into the optical assembly and command the computer to search its library for a matching spectrum.

From the foregoing presentation of alternatives, it would seem that the optical systems should be preferred from the standpoint of simplicity. As always, however, there are problems inherent with optical systems which theory does not

address. The primary areas of concern in this application can all be grouped into the category of mechanical alignment. There is degradation in optical systems in general from imperfections in lens and focal plane geometries. This specific application requires in addition that careful attention be paid to image positioning and size on the transparencies. A perfect match of signatures requires not only that the signature characteristics be matched and clearly discernable, but also that the signature image on the object transparency be identical in size, position, and orientation to the image. This latter requirement means that in the case of the purely optical processor, the object transparency must be centered on the lens axis and rotated through 360 degrees to determine the best signature correspondence orientation. All of the above considerations place accuracy requirements upon either the photographic step or the optical system operator's placement of the transparency, thereby defeating our intention to develop a fast efficient system.

The all-digital system is somewhat cumbersome when the microdensitometer is remembered, but it provides the most accurate and flexible processing available. Since it is not clear initially what degree of resolution will be required to match signatures with the accuracy desired, it is prudent to perform the initial research with as much accuracy and flexibility as possible. Therefore, the research described herein is done with the digital system with intent to determine performance capability of an "optimum" system. This optimum or baseline system will be used in future work to perform statistical measurements as functions of several parameters. From these measurements, it should be possible to establish minimum performance requirements for use in determining feasibility of the optical techniques.

III. DATA EXTRACTION

Digital processing of the ballistics signatures begins by sampling and digitizing the phototransparencies made using the conical reflector. These transparencies are "negatives", one of which was used to produce the positive print in Figure 3. Since the signature information is found in a two-dimensional pattern, two-dimensional sampling is required. The scanning microdensitometer used to sample and digitize the signature transparencies is programmed to perform two-dimensional sampling. It consists of a glass table which can be positioned in X and Y coordinates with a resolution of 1×10^{-6} meter (1 μ M) and an adjustable aperture collimated light source which projects a beam through the table into a detector. In operation, the transparency is measured by the detector at every sample point. The detector output is digitized by an analog-to-digital (A to D) converter and the resultant digital density values for each point are stored on magnetic tape together with the coordinate values.

The location of the planar sample function on the transparency is established by defining the origin for the microdensitometer's Cartesian coordinate system such that the entire bullet image is just contained in the first quadrant, as limited by the maximum coordinate values. The maximum values are the same for both X and Y coordinates and are defined primarily by the sample spacing. The maximum allowable spacing must be determined from the data bandwidth to reduce data storage requirements. Maximum sample spacing can be determined graphically in this application with the aid of a calibrated microscope and a representative group of transparencies. The signature negatives are surveyed to establish the minimum width of a signature line. This measurement must

be made at the inner-most part of the signature. The reason is clear when the image mapping mechanism is considered. Figures 2 and 3 demonstrate that the gun barrel signature as embodied in the cylindrical surface of the bullet is mapped into an annular image by the truncated conical reflector. If the bullet is positioned point outward as in Figure 2, the base will be mapped along the inner edge of the annulus while the point appears as the vaguely defined outer edge. Signature lines of constant width along the length of the bullet are mapped into radial lines of constant angular width in the annular image. Therefore, a signature line in the image is narrowest at the end closest to the center of the reflector, which is the inner edge of the annulus and corresponds to the base of the bullet. A sample spacing chosen to capture the smallest signature lines in this area will certainly suffice at all points for all lines in the signature image. The criterion for choosing a maximum sample spacing can be understood with the aid of Figure 5. Figure 5a is a simplified diagram of the sample locus for a

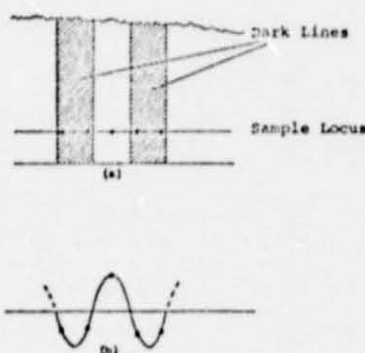


FIGURE 5
IMAGE SAMPLING DIAGRAM

single scan along the inner edge of the image annulus displayed in an area where it is normal to two dark minimum width signature lines separated by a bright line. The objective is to

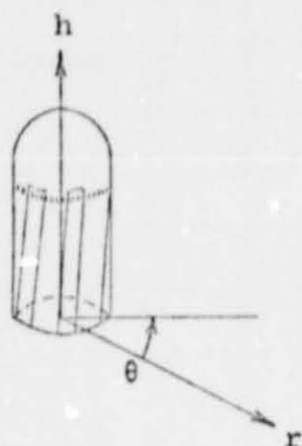
space sample points, indicated by dots on the locus, so that none of these lines are skipped; and this is accomplished as indicated for the worst case if the points are spaced slightly closer than the width of the narrowest line. This graphic criterion is equivalent to the Nyquist criterion, or what Bracewell [2] calls "critical sampling" as can be seen in Figure 5b. The sinusoid in part b represents the transmitted light intensity, or Z amplitude, of the lines in part a with the corresponding sample points indicated. The Nyquist criterion, simply stated, says that the sampling frequency must be slightly greater than twice the maximum frequency present in the analog signal, and clearly it is met.

The foregoing analysis serves to ascertain that the desired signature bandwidth will be preserved in the sample data, but it does not assure that the image on the transparency is bandlimited below the Nyquist frequency, as it must be to prevent aliasing of high frequency components into the signature band. The microdensitometer can perform a low-pass filtering function on the image data before it is sampled, however, by averaging with the adjustable beam aperture. If a square aperture is selected whose width is equal to the sampling interval, then each sample will represent the average of all image points in the beam and these averaging areas will be exactly contiguous. This scheme efficiently serves as an anti-aliasing filter.

After the bullet image is X-Y sampled and digitized it will be used in several ways for comparison with other images, notably by correlation. If the two-dimensional correlation process is pictured graphically as sliding one image around over another while plotting the sum of products of all pairs of sample points for each relative position of the images,

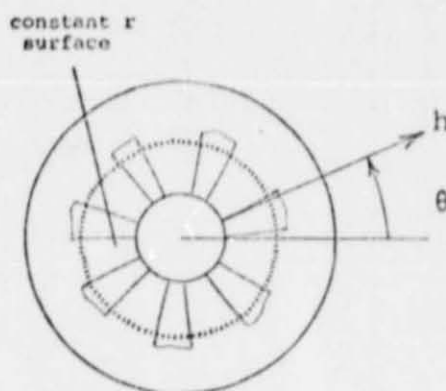
it is obvious that some serious problems exist. The most obvious is that there are too many multiplications required. A typical sample array contains 1024×1024 words, an overwhelming size for correlation processing. A still more serious problem appears when one considers that two-dimensional cross-correlograms are functions of X and Y lags only, containing no information about relative image rotational alignment. Although it is practical to center the images in X and Y before they are sampled, there remains the problem of performing two-dimensional correlation as a function of rotational lag on X-Y samples arrays. Such a process would require interpolation to locate corresponding samples in the two arrays as one is rotated.

If the sample spacing criterion is recalled, the bullet image is oversampled everywhere except along the inner edge of the annulus, which indicates that possibly the data volume could be reduced. Figure 6a is a diagram of the bullet located in a cylindrical coordinate system, and part b diagrammatically shows the bullet with cylindrical coordinates as mapped by the conical mirror. It is apparent from Figure 6b that the digitized X-Y image can be resampled in h - θ coordinates so that a sample array resembling Figure 6c results which is in essence the signature unwrapped from the bullet. The h and θ sample spacing is chosen equal to the original X-Y increments at the inner edge of the annulus where it crosses the X-axis so that the maximum sample spacing is obtained throughout the image. The image center is determined manually on the microdensitometer and routinely defined to be 512, 512 in the X-Y coordinate system. Resampling is accomplished by defining a "ring" of θ -points for each incremental h value and interpolating the sample values at these points from the X-Y sample array. Since only the side of the bullet contains signature information, the h -axis can be truncated to eliminate the crimp



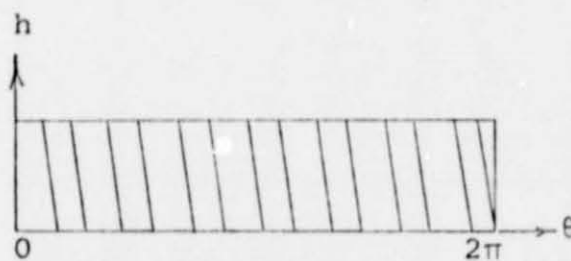
(a)

BULLET REPRESENTATION IN
CYLINDRICAL COORDINATES



(b)

PROJECTED SLUG
REPRESENTATION WITH
CYLINDRICAL COORDINATES



(c)

RESAMPLED DATA ARRAY GEOMETRY
(Truncated below crimp band)

FIGURE 6
CYLINDRICAL PROJECTION REFERENCE DIAGRAM

ring around the bullet near the point as well as the point itself. This is a very useful capability since it is common to recover bullets damaged on the front end. Figure 7 presents a useful illustration of the resampling process. It is a contour plot of a small portion of a bullet image interpolated from the X-Y sampled data as digitized by the microdensitometer. The contour lines enclose local amplitude peaks, or bright areas from the planar bullet image. Superimposed on the contour plot is a constant-h resampling locus corresponding to a ring around the bullet approximately halfway between the base and the crimp band. Figure 8 is a plot of the amplitude samples interpolated along the same locus shown in Figure 7 and to the same scale. These new samples are representative of the data present in the rings after resampling.

Another consideration encountered when extracting data with a microdensitometer from images recorded on photographic film is the transfer function of the film. Kodak [3] explains that within the linear portion of the film characteristics curve photographic emulsions darken in proportion to the logarithm₁₀ of the intensity of incident light. The exact relationship is expressed as

$$D = \text{Log}_{10} I$$

where D is optical density and I is intensity. A microdensitometer of the type used in this research commonly reads out this digital density as it scans the transparency. Since density represents the logarithm of the original image intensity, considerable dynamic range compression is present. This compression reduces accuracy in all of the contemplated processing techniques because of its non-linear filtering effect. To avoid non-linearity density is converted back to intensity, but the

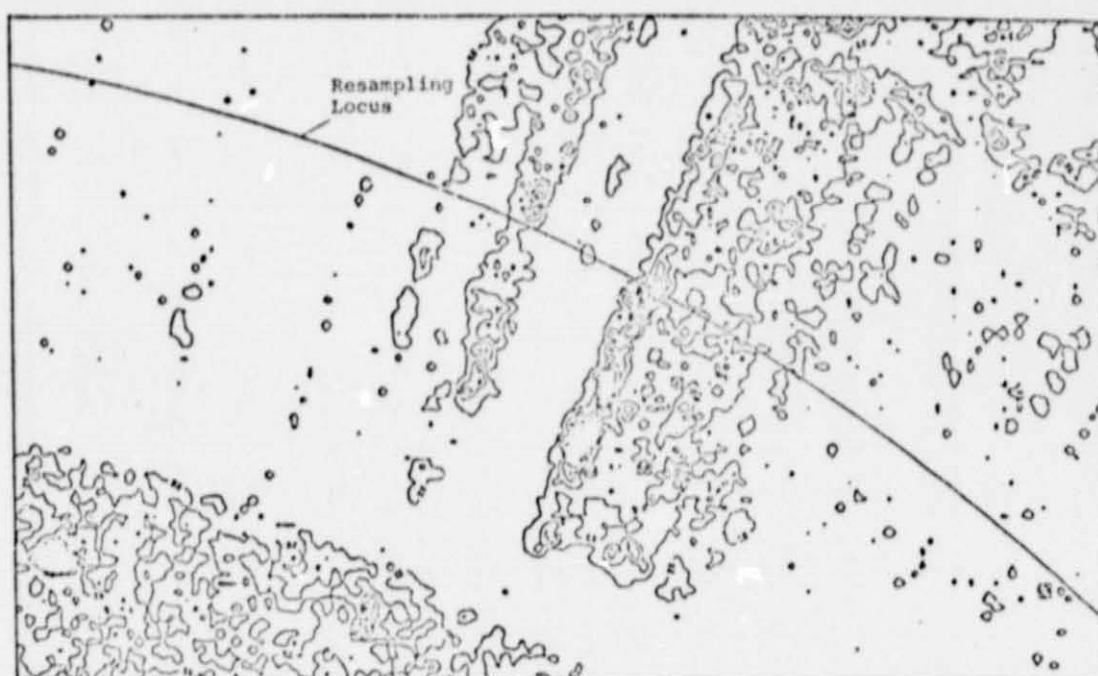


FIGURE 7

CONTOUR PLOT OF A PARTIAL X-Y DATA ARRAY

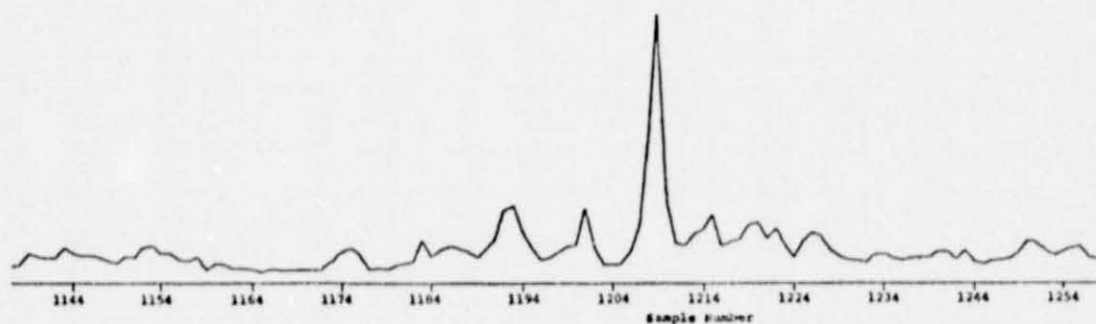


FIGURE 8

INTENSITY AMPLITUDE PROFILE FROM X-Y DATA ARRAY CONTOUR

conversion must be performed before resampling since linear interpolation of density values does not produce linearly interpolated intensities.

Another observation can be made contrasting the X-Y and h- θ sampled data representations. The X-Y format of the image data requires two-dimensional processing for all signature comparison schemes because of the annular shape of the signature region in the X-Y plane. In the h- θ plane, however, the signature occupies a rectangular region. Moreover, reflecting on Figure 6c, it seems likely that sufficient information to compare signatures can be found in the relative positions of lines of the signature, described as a function of θ alone. Resampling conceivably reduces the two-dimensional problem to one dimension.

In contemplating the one-dimensional approach, additional raw data preparation steps appear advisable. The contour plot in Figure 7 demonstrates that signature lines are not of constant amplitude along their lengths, and in fact, some even approach zero amplitude in places. This problem suggests that heavy averaging in the h dimension might be useful. This would remove h-dependent high frequency information, but the one-dimensional scheme presumes that very little h-dependent signature information exists. If very many rings are to be averaged together, however, some deskewing must be done to compensate for the twist imparted by rifling to the signature. This rifling twist prevents the signature lines from being strictly parallel to the h-axis, but the skew is linear with h and easily measured. Combined with the other gross characteristics such as caliber and number of grooves skew or twist makes an excellent signature library categorization clue.

Admittedly, one-dimensional analysis does not provide intermediate outputs that are directly comparable to those from the optical processors being considered. Of particular interest would be the power spectrum output for comparison with the optical power spectrum processor output, but a basis for performance prediction will still exist. The one-dimensional power spectrum should provide a worst-case test for power spectrum based processors, and should it prove to be a useful signature discriminator, the optical version should work at least as well.

IV. EXPERIMENTS AND RESULTS

The research conducted for this project is part of a joint effort funded by the National Aeronautics and Space Administration (NASA). The photographic signature recording was done by Grumman Aerospace Corporation using the reflective cone assembly previously described. Only the digital processing approach was to be investigated by UNITECH in Phase I of the project, using a number of phototransparencies digitized with 12-bit resolution on Perkin-Elmer model 1010A microdensitometer systems located both at NASA's Johnson Space Center (JSC) and at the University of Texas at Austin. Signature analysis was performed with a microscope equipped with a calibrated ocular micrometer on the 35 mm transparencies, from which it was determined that a square sample grid of 1024 x 1024 points would be required to assure adequate image resolution. After sampling, the digitized image densities were converted to linear intensity values and resampled in h and θ increments chosen to maintain equivalent image resolution. The resulting image sample array contains 58 rings spaced at uniform h increments up to but excluding the bullet crimp band. Each ring contains 1458 samples uniformly spaced in θ . The exact number of θ increments chosen was determined from processing speed considerations inherent in the transform processing next to be introduced.

One of the early concerns about the digitized image was the bandwidth of the signature. A quick check can be made using the power spectrum of one or more rings since little or no high frequency signature information is expected to exist as a function of h . The power spectrum can be obtained from the Fourier transform of the ring data function, since

$$P(f) = R \times R^*$$

where

$$R = F[r] ,$$

and R^* is the complex conjugate of R . This method for obtaining the power spectrum is practical because of the speed of current Fast Fourier Transform (FFT) algorithms. The fastest ones available require that the number of input samples be an integer power of two, but in this application such a constraint was judged hazardous, at least until the useful bandwidth of the signature could be determined. The minimum radius of the signature annulus as sampled by the microdensitometer is 231 increments long which means that the first ring has a circumference of 1451 increments. Rather than undersample at 1024 points per ring, it was decided to use a mixed-radix FFT and the one described by Singleton [4] was selected. Its speed depends upon the prime factors of the array length integer, and 1438 is the closest integer to 1451 permitting efficient FFT operation, thus 1458 became the ring array size. Figure 9 is an unnormalized power spectrum generated from a representative sample ring after transformation using the FFT. It was plotted as a single-sided spectrum and extends from a spatial frequency of 1 to 729 cycles per revolution (CPR) which is the folding or Nyquist frequency. The dc component was removed, but no ring power spectrum averaging or other smoothing was done since the only objective was to roughly determine the signature bandwidth. Obviously it falls well within the 729 CPR band, and it seems doubtful that any important components exist above 364 CPR or half of the current bandwidth.

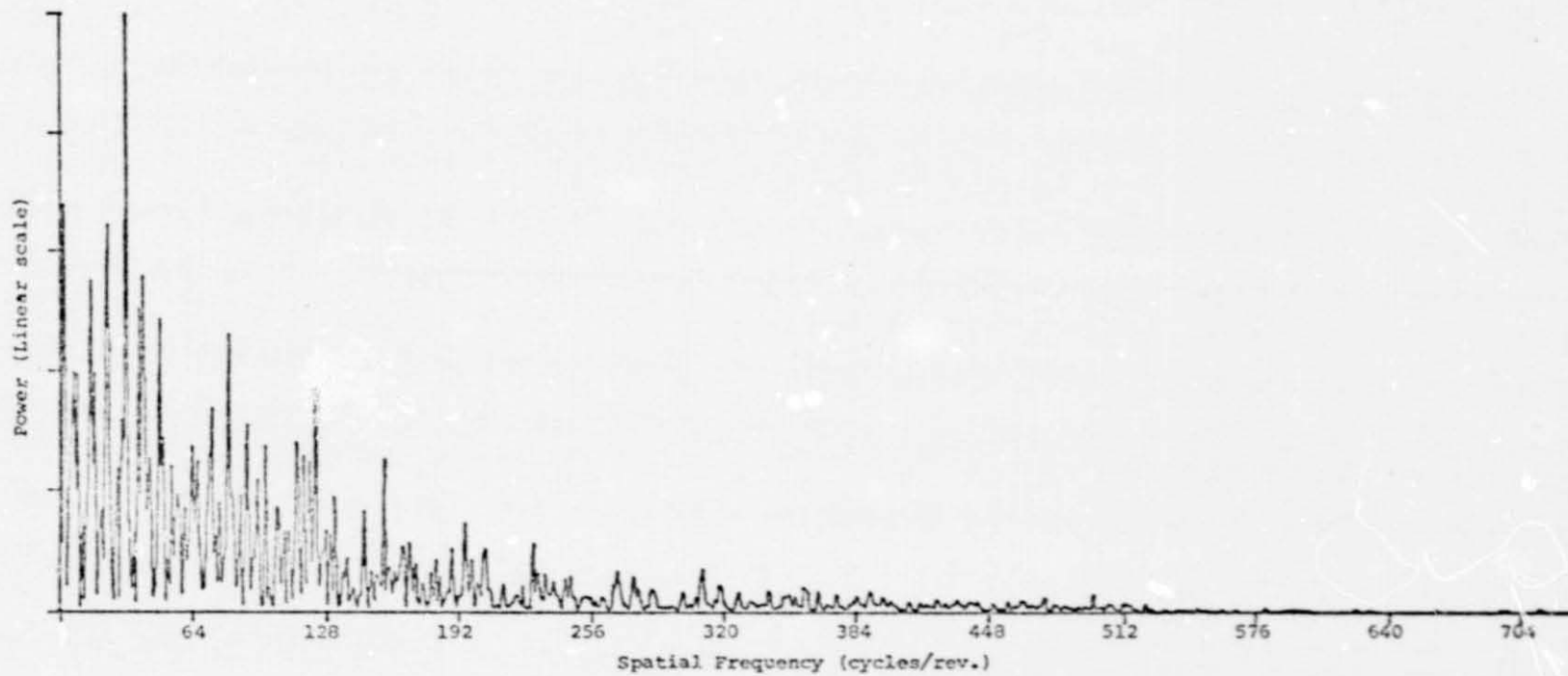


FIGURE 9
UNNORMALIZED POWER SPECTRUM PLOT
OF A SINGLE DATA RING

Given the above information it is reasonable to reduce the ring array size to speed up processing. Since the original bandwidth was twice that deemed necessary, it was decided to average and decimate the ring data samples by two. Averaging pairs of samples effectively halves the bandwidth to prevent aliasing so that only half of the original number of ring data samples must be used, specifically the averages of the original pairs.

The next technique to be investigated was the previously mentioned averaging of data rings as an aid to one-dimensional processing, using θ -dependent information alone. Prior to averaging a large number of rings, an effort was made to measure the skew present as a function of h . The method used consists of averaging the first and last five rings to provide two separate rings representative of signature data at opposite ends of the bullet, and then cross-correlating these rings to measure the rotational lag or skew between them. Again making use of the FFT, the cross-correlogram is expressed as the inverse transform of the complex cross-power spectrum of the two rings.

$$F^{-1}[R_1^* \times R_2] = \phi_{12}(\tau)$$

Using Lee's notation [5], a positive lag, τ , corresponds to a positive rotation of ring 2 with respect to ring 1. Figure 1C is the correlogram which was generated for bullet A-4 except that the DC component was removed from the cross-power function. Two particularly disturbing bits of information appear in this plot. First, there is very little skew measurable between the rings as indicated by the location of the peak near the origin on the τ axis. Second, the next highest peak is comparable in size to the main peak. These observations prompted a closer examination of the ring sample function to find the explanation.

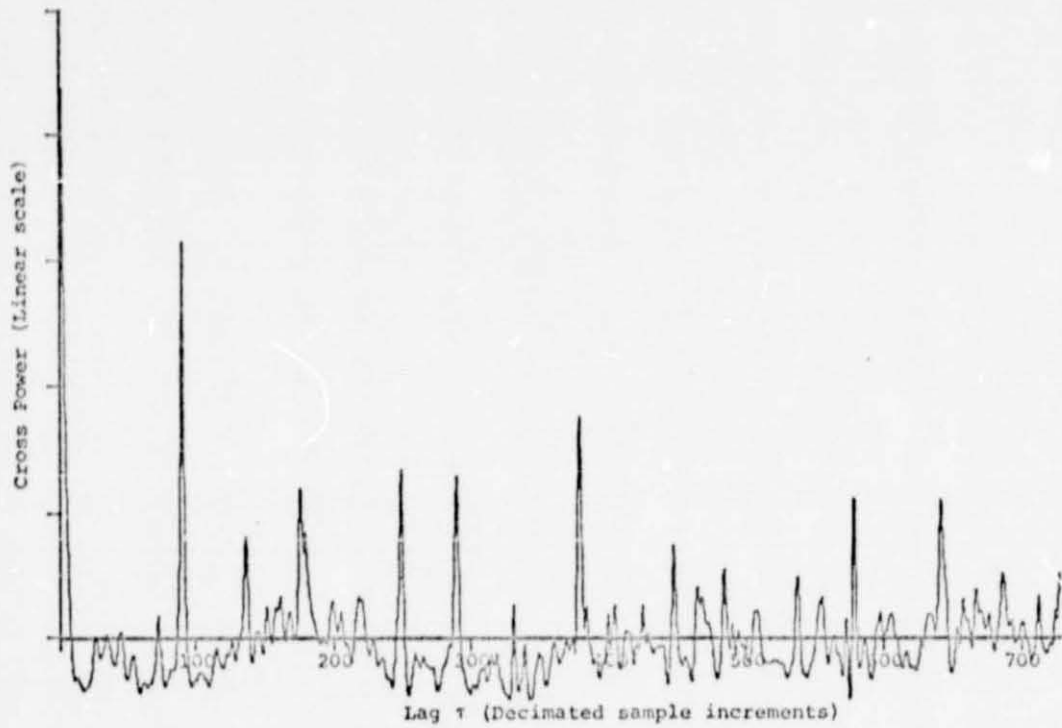


FIGURE 10

UNNORMALIZED CORRELOGRAM OF WIDELY-SEPARATED
FIVE-RING AVERAGES FROM BULLET A-4

Figure 11 is an intensity plot of the lower of the two five-ring averages. The large amplitude spikes correspond to the brightest signature lines in the image which emanate from the edges of the rifle grooves. Since there are five grooves, there are ten edges which should produce ten equally spaced spikes. Several of them are missing, and a re-examination of Figure 3 shows them to be missing in the image, probably due to non-uniform lighting when the transparency was made. The extreme amplitude disparity between the groove boundary spikes and the remaining signature structure suggests that the correlogram in Figure 10 is dominated by spikes. The effect of this domination is that if the correlation peak amplitude were to be used as an indication of signature similarity, then any two signatures with the same rifle groove pattern would be judged virtually identical. This conclusion is supported by the observation in Figure 10 that a very high correlation peak occurs at a lag value equivalent to a misalignment of one groove width. Fortunately, at least one simple solution exists for this problem. If the spikes are limited or clipped at a very low amplitude, the secondary peaks should disappear from the correlogram. This solution is supported by Figure 12 which displays the correlogram generated using clipped ring data.

The cause of the poor skew indication in Figures 10 and 12 was not clear at this point in the research. The amplitude of the normalized peak is less than 0.5 instead of almost 1.0 as had been desired but some correlation reduction might be expected if the signature structure is not totally independent of h as this one-dimensional analysis assumes.

The next step performed was cross-correlation of averaged rings from signatures of two different bullets fired from the same gun. The normalized peak value of this correlogram was expected to give some indication of the degree to which

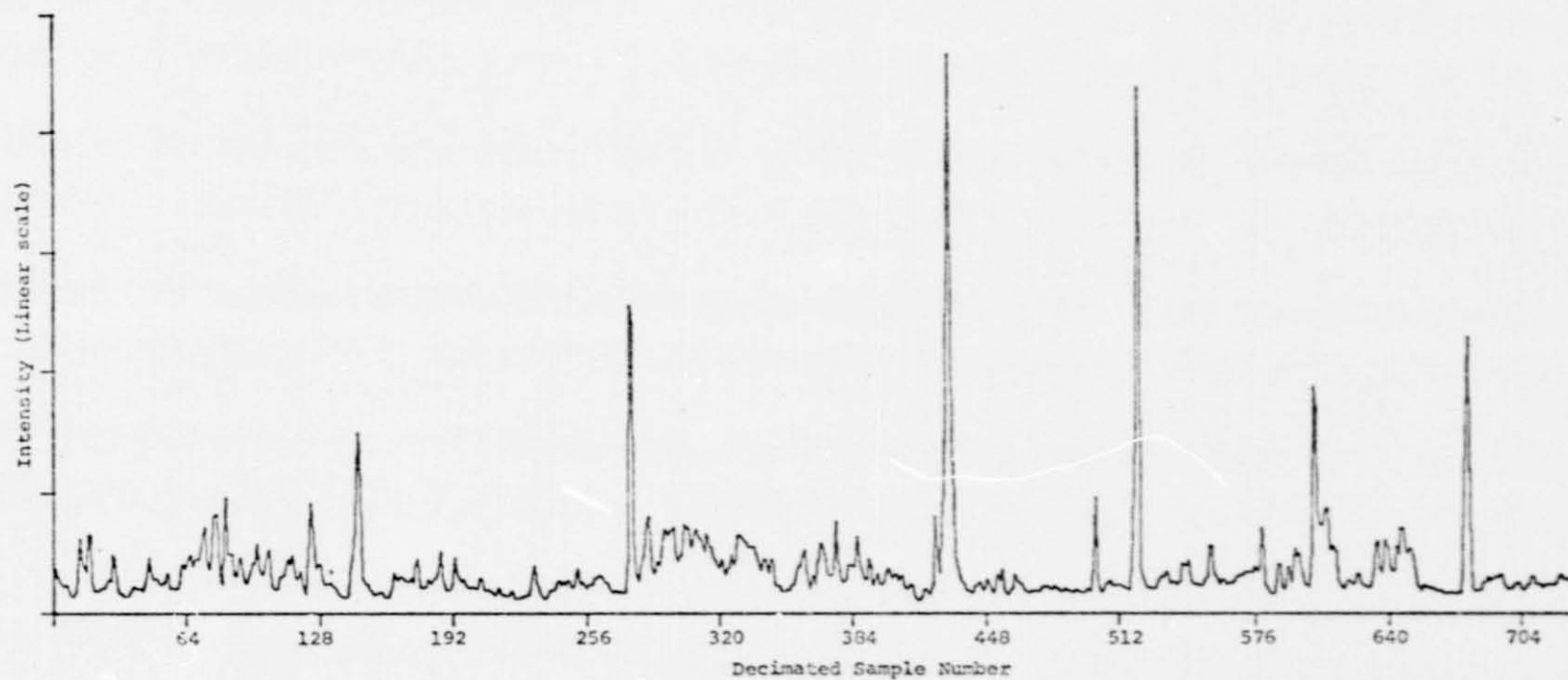
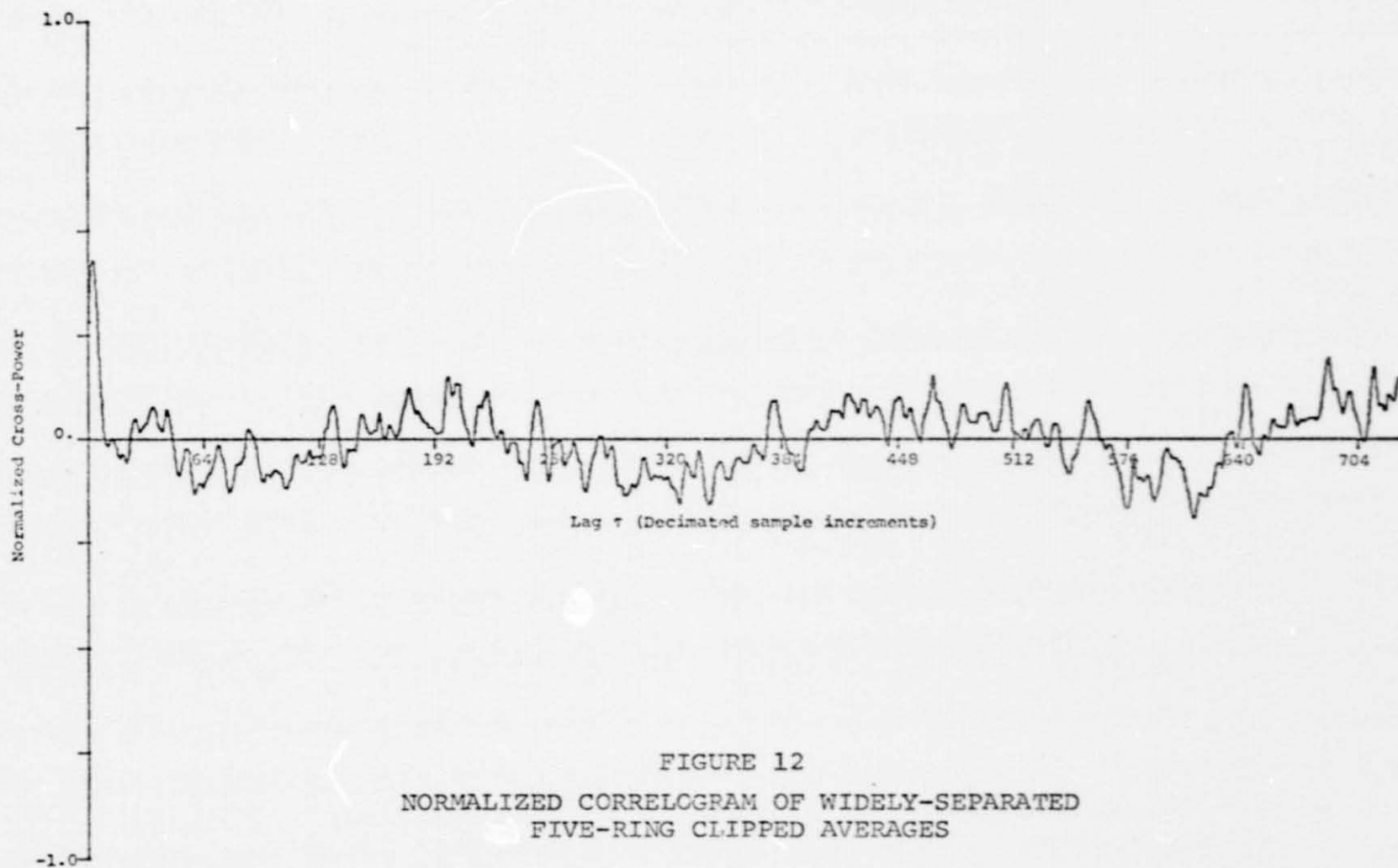
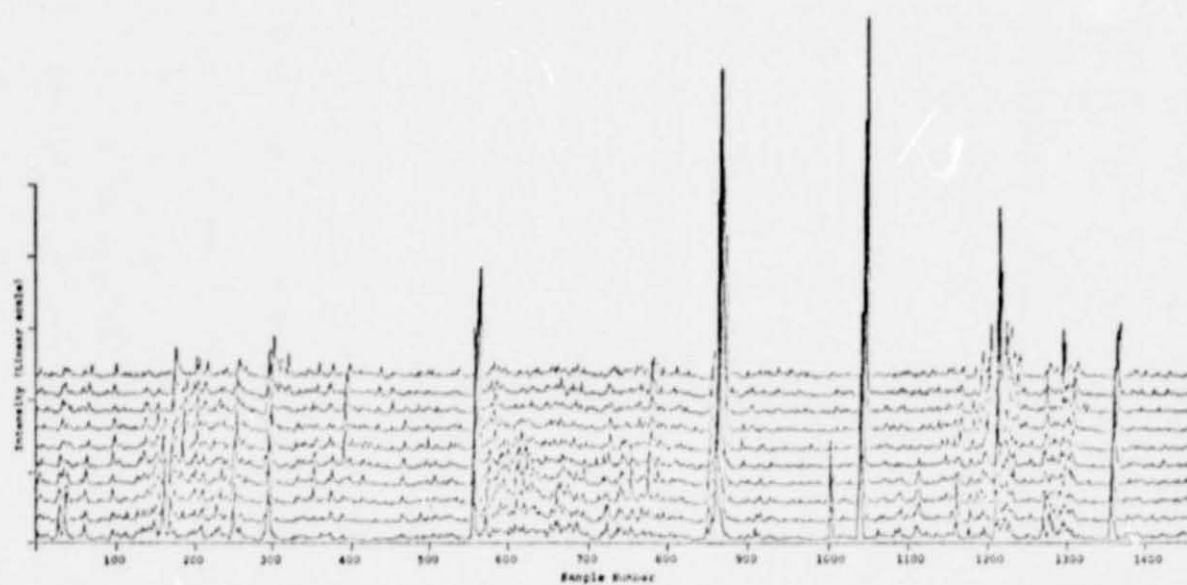


FIGURE 11
INTENSITY PLOT OF A FIVE-RING AVERAGE



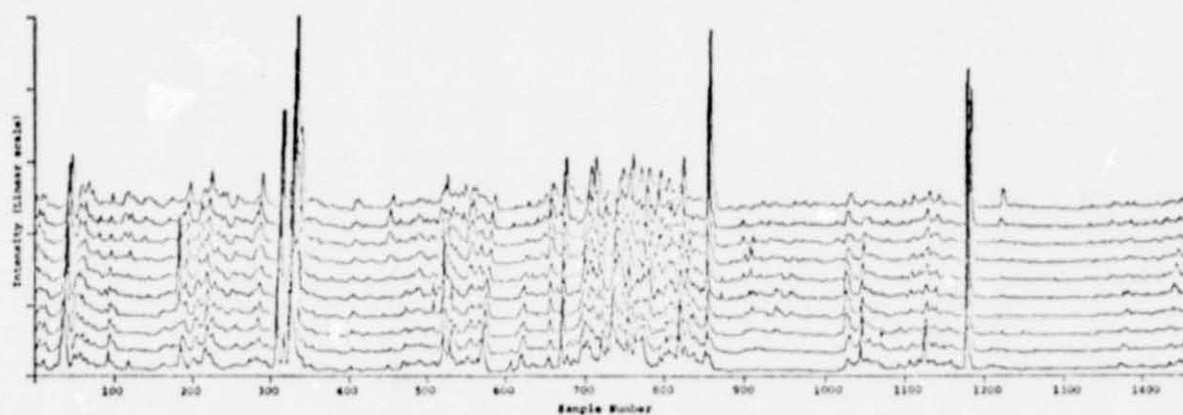
test fired bullet signatures would match and thus suggest where the match detection threshold might be set. Because the skew measurement had been questioned, ensembles of the individual rings to be averaged were plotted for each signature image. The ring plots were stacked one above the other to determine how much signature structure might be lost in the ten-ring average, and whether or not any deskewing would be required. These plots are found in Figure 13. In these plots several observations are important. First, although good comparison of the two signature ensembles is not expected at zero lag, it appears that they do not compare at any lag value. It had been expected that at least the unclipped groove spikes would match at ten different relative orientations, but they do not. When measurements were made of the spacing between spikes in each of the bullet signatures, and allowing for missing spikes, they were found to be very non-uniform. Furthermore, close inspection of the skew across the ensemble for each spike shows that the skew is non-uniform among the groove spikes within the same signature, which probably explains the poor performance of the skew correlogram. This distortion of gross image structural features can always be expected to ruin correlation processing, and indeed in Figure 14 the cross-correlogram using these averaged, but clipped ring ensembles has no primary peak at all.

A close examination of photo enlargements of the transparencies from bullets A2 and A4 showed that the angular width of rifle grooves in the images is irregular, and moreover, that the rifle groove pattern on one photo cannot be matched with the pattern on the other because of some angular distortion. Furthermore, these are signature patterns from two bullets which had been found to match closely when visually observed under a comparison microscope. Based on these observations, it was postulated that some misalignment in the photographic step



(a)

TEN-RING ENSEMBLE PLOT OF INTENSITY DATA FROM BULLET A-4



(b)

TEN-RING ENSEMBLE PLOT OF INTENSITY DATA FROM BULLET A-2

FIGURE 13

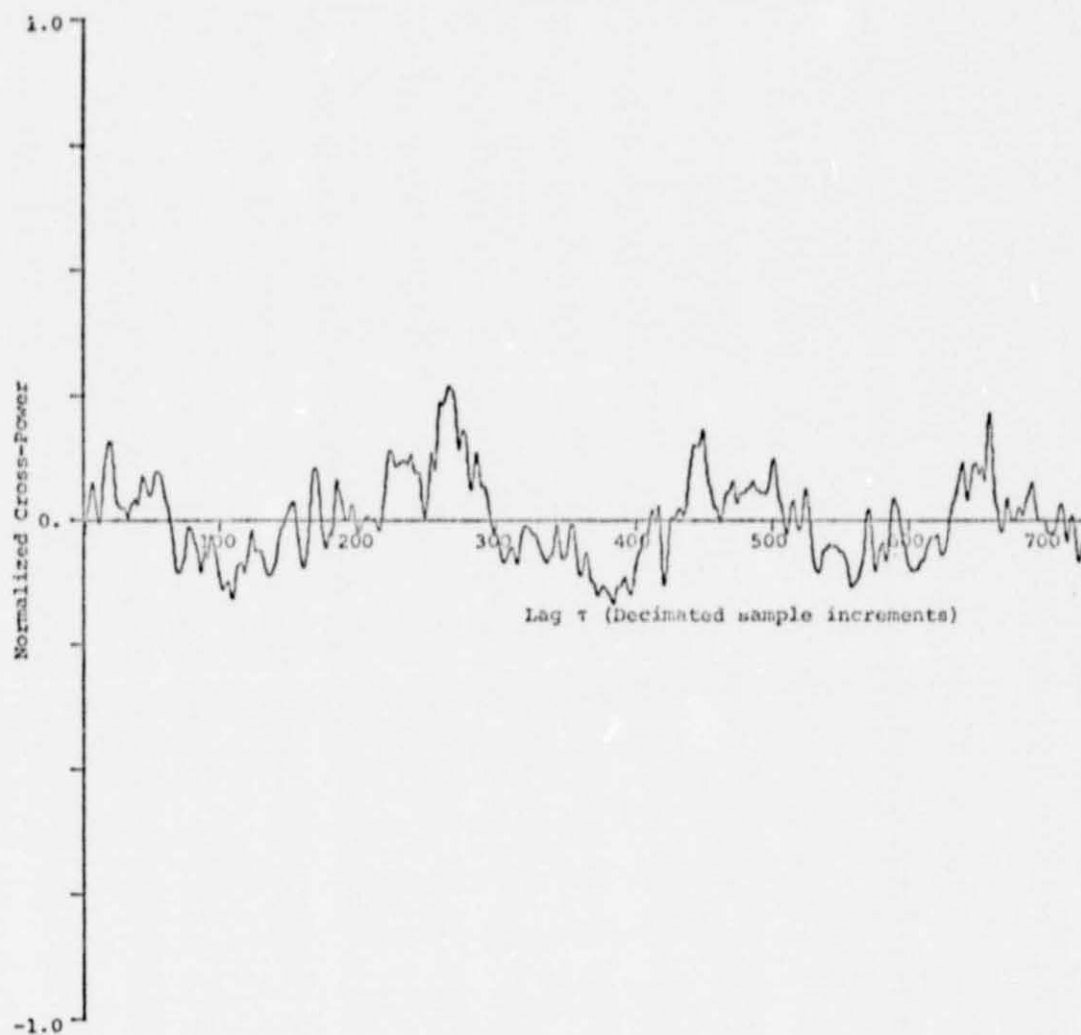


FIGURE 14

NORMALIZED CROSS-CORRELOGRAM OF TEN-RING AVERAGES
FROM BULLETS A-2 AND A-4

superimposes an angular distortion function onto the signature image. The orientation of this function relative to the rotational position of the bullet varies from one bullet to the next since no attempt is made to rotationally position each bullet in the cone the same way. If this explanation were indeed the cause of the problem, it was reasoned that two photographs made of the same bullet without moving anything should exhibit signature images distorted in exactly the same manner, and cross-correlating the two should produce a well defined peak at zero lag. Fortunately such a pair of phototransparencies had been made as a test of exposure settings, and the resulting cross-correlogram is presented in Figure 15. The fact that the expected peak is present vindicates all of the digital processing steps, including the resampling process which would have been the next logical suspect. However, this discovery halted further signal processing analysis pending resolution of the photographic problems. Subsequent visual observation of a bullet in the conical reflector has demonstrated that the type of distortion encountered in the transparencies is produced when the camera lens is not centered on the axis of the cone, but no improved transparencies have been made at this time.

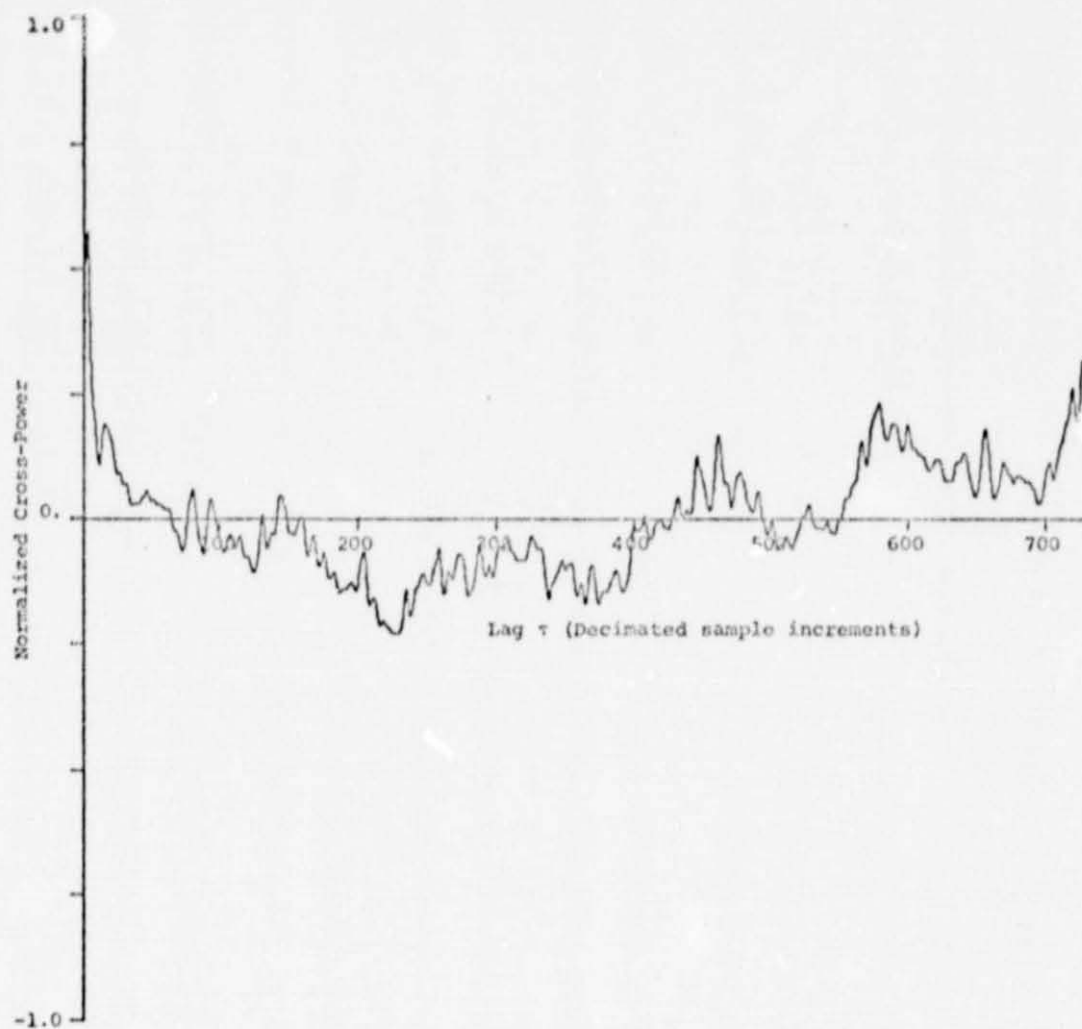


FIGURE 15
NORMALIZED CROSS-CORRELOGRAM OF TEN-RING AVERAGES
FROM TRANSPARENCIES 7A AND 9A

V. SUMMARY AND CONCLUSIONS

Research reported herein has applied some common digital signal processing techniques to the problem of recognition of gun barrel signatures imparted to fired bullets. Primary tools utilized have been spectral analysis and correlation analysis, both of which were implemented with the aid of the Fast Fourier Transform (FFT). Signature extraction was accomplished, with as yet only moderate success, by photographing the signature image as projected onto a plane by a conical reflector. Since both digital and optical processing can be applied to the resulting phototransparencies, it was hoped that the highly flexible digital approach would provide a reference level of performance which might be used to evaluate simpler or faster optical or hybrid systems. Unfortunately only a cursory evaluation of the digital techniques mentioned has been possible due to aberrations in the optical components of the photographic system which severely distorted the signature images.

The processing techniques described herein have demonstrated encouraging capability. With little or no frequency domain filtering it is possible to produce correlograms with well defined peaks. The power spectra of representative signatures are well behaved, and the sampling scheme developed permits ensemble averaging of power spectra to support meaningful spectral analysis. As soon as a practical method is developed to produce accurate signature transparencies, this effort should prove successful.

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